



Navigator Program Science Overview

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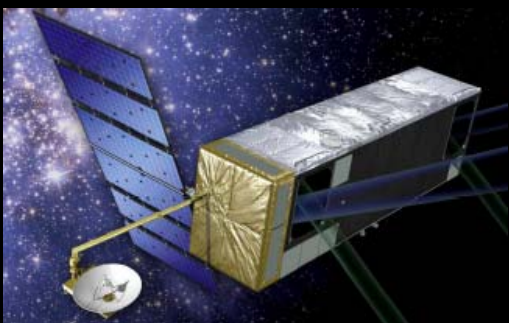
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Abstract

NASA's vision for exploration encompasses detecting and characterizing planets like the Earth beyond the solar system (exoplanets), and searching for life on them. In response to this challenge, we the scientists of the SIM, TPF-I, and TPF-C Science Teams, in conjunction with NASA's Navigator Program, recommend the following actions to achieve these ambitious goals:

- Launch SIM in 2015. Will detect nearby exoplanets, and measure masses & orbits.
- Launch TPF #1 in 2019 (C, I, or O; full-scale, mid-scale or probe-scale) with TPF #2 to follow. Will detect nearby exoplanets, characterize surfaces and atmospheres, and search for signs of life.
- Continue cooperation with ESA and other international partners to achieve these goals.
- Support ground and sub-orbital observations, lab work, research and analysis, and theory.

1. Introduction

Detecting Earth-like planets with signs of life would be historically transforming. Today it is within our reach to make these discoveries and NASA has developed the Navigator Program (NP) to carry out this endeavor. This white paper captures the collective recommendations of several hundred scientists and engineers who have investigated how to achieve this inspiring goal, through numerous studies, experiments, and workshops organized by the NP over the past several years.

The primary goal of the Navigator program is to detect Earth-like exoplanets and discover if life does indeed exist there. The Space Interferometer Mission (SIM) is a crucial first step in this process, and the Terrestrial Planet Finder (TPF) missions are the second step. These missions are fully discussed in separate white papers. We note here that there are three different versions of TPF (coronagraph (C), external formation-flying occulter (O), and interferometer (I)) that appear capable of carrying out the required measurements for *detection* and *characterization*. By about 2011 we should have, from the SIM, CoRoT (CNES/ESA), and Kepler (NASA/Discovery) transit missions, the necessary scientific knowledge about the general abundance of terrestrial planets as well as the requisite technical experience from ongoing laboratory testbeds to initiate the first of these missions "TPF #1." The selection of which version of TPF to fly first, by 2019, will be driven by mission capability, technology maturity, available funding, and the status of international collaborations. As discussed below, information on the number and nature of the planetary systems associated with specific nearby stars will be available through observations with SIM in time to enhance the scientific return from TPF #1.

2. The State of Exoplanet Science

Of the 200-plus known exoplanets, 94% were discovered using the radial-velocity (RV) technique, 3% by transit photometry, 2% by gravitational microlensing, 2% by direct imaging, and 2% by pulsar timing. The recent discovery rate is about 30 exoplanets per year. This rate seems to be limited by instrumental sensitivity, not the number of planets. About 15% of these planets reside in multiple-planet systems, providing hope that we may someday find analogs to the Solar System. Some other basic statistics are as follows.

- The median planet mass is about $450 M_{\text{Earth}}$ with a distribution, dN/dM , that rises sharply ($\propto M^{-1}$) to lower masses. We expect that many more small planets exist and will be detected as soon as more sensitive techniques are employed.
- The median semi-major axis is about 0.8 AU, much smaller than the 5-30 AU in our system, suggesting that systems like ours are yet to be discovered.
- The median distance of these stars is about 36 pc, telling us that many nearby stars have planets.

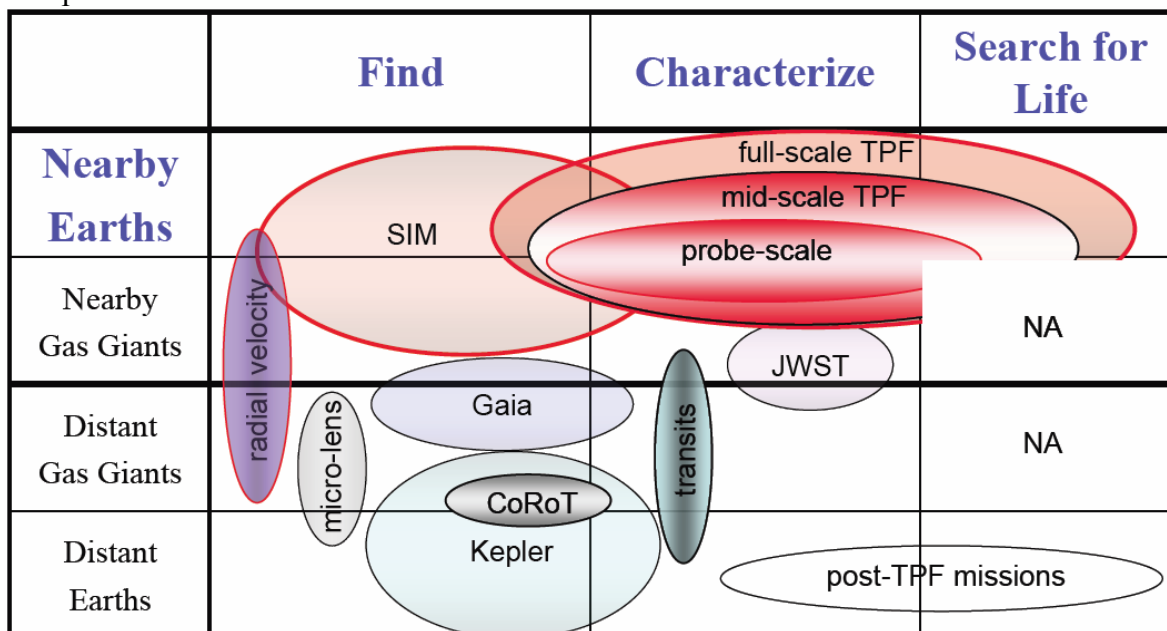


Figure 1. Some of the techniques and specific projects to find exoplanets are shown in relationship to their main types of targets and whether the goal is to find, characterize, or search for life on that planet. Here “nearby” means 5-30 pc from the Sun, and “distant” means 30-1000 pc, roughly. The gas-giant category includes hot Jupiters.

What do we *not* know about these exoplanets? The answer is, “almost everything”. The purpose of the NP is to find the missing pieces of the puzzle. Here are some things we do not know, but which could be discovered through NP and related missions:

- We do *not* know the fraction of stars (η_{planets}) that have planets of any kind. The CoRoT and Kepler transit experiments and SIM astrometry will each contribute to this important number.
- We do *not* know the exoplanet mass distribution function $dN/dM = \xi(M)$ down to Earth-mass range, but the evidence to date shows that this function increases dramatically to lower masses. CoRoT, Kepler, and SIM will each make much-needed contributions.
- We do *not* know the average density of most exoplanets. Detections of transiting planets with CoRoT and Kepler, augmented by masses determined through radial velocity measurements with ground-based telescopes will provide this information.
- We do *not* know the fraction of stars with terrestrial planets in the habitable zone, here called somewhat loosely η_{earth} . CoRoT, Kepler and SIM are needed.

- We do *not* know the typical intensity of emission from exozodiacal dust clouds. Spitzer and Herschel will probe cold dust, and the Keck Interferometer (KI) and Large Binocular Telescope Interferometer (LBTI) will inform us about material in the habitable zone.
- We do *not* know anything about the colors or spectra of the vast majority of exoplanets, in the visible or infrared. We need TPF #1 and #2 for this.
- We do *not* know about atmospheres, circulation, clouds, surfaces, or variability of these quantities. Follow-up of transiting systems with Spitzer and, eventually, JWST will begin this investigation, but we need TPF #1 and #2 for a complete study.
- We do *not* know anything about habitability or signs of life on any exoplanet, or if there are any Earthlike exoplanets. We need TPF #1 and #2 for this.

The unique capability of each mission is shown schematically in Figure 1, and the approach for planet characterization is shown in Figure 2.

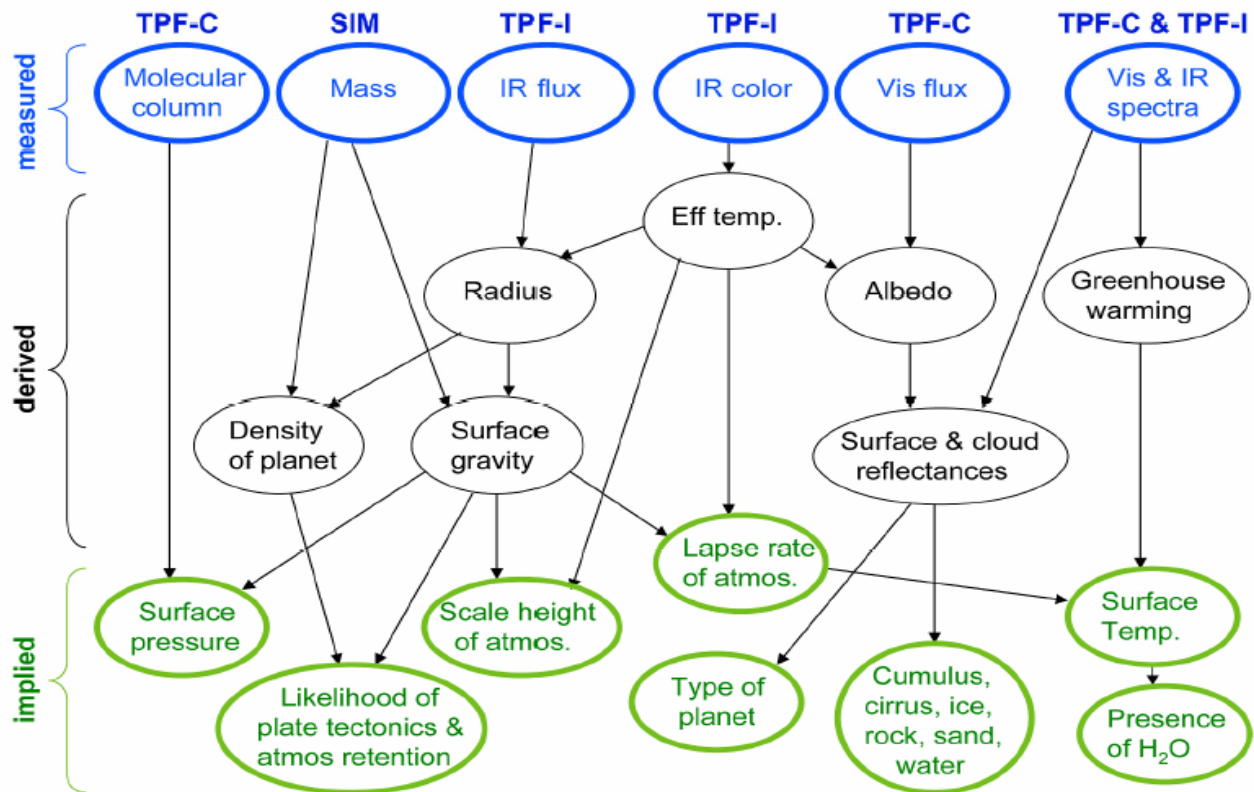


Figure 2. The synergy between Navigator missions, SIM, TPF-C and TPF-I, leads to full characterization of exoplanets. The flow-down from mission data to derived properties and finally to the inferred physical properties of an exoplanet is shown schematically in this diagram. For example, TPF-I will measure a planet's infrared flux and color, from which the effective temperature and radius can be derived. Then using SIM's measurement of mass we can derive the mean density and surface gravity of the planet. Finally, these derived quantities can be used to imply whether a planet could have plate tectonics, and also whether it could retain its atmosphere. A similar diagram shows how signs of life can be implied from measurements by SIM, TPF-C/O, and TPF-I.

3. Role of the NASA's Navigator Program

The main missions and projects of the NP are the Space Interferometry Mission (SIM), TPF-C/I/O, KI, LBTI, and the Michelson Science Center (MSC). The NP also supports exoplanet-related university research, technology development at Universities, NASA Centers and industry, science working groups, conferences, workshops, and publications. Future Exoplanet missions, from large- to probe-class, would be run as NP missions. As is the case with most of NASA's astrophysics missions, the instrumentation and science programs for NP missions would be openly competed. In the following section we discuss potential future missions.

4. Exoplanet Science Missions

Figure 1 shows the extent to which major exoplanet missions will be able to observe terrestrial exoplanets (here "Earths") and gas giants (including "hot Jupiters"). We are particularly interested in nearby Earths because these can be followed up in depth. The only way to investigate the full population of nearby Earths is to launch SIM and TPF #1 in either the full-scale version, or if terrestrial planets are abundant and funding dictates, in a mid-scale or probe-scale version.

To show explicitly how these observations could be applied to characterizing a nearby Earth-like planet, Fig. 2 shows measured quantities (mass, visible color, etc.) for SIM, TPF-C, and TPF-I. Here the spectroscopically similar TPF-C and -O are combined. This figure shows that all three missions are needed to derive properties and characteristics of a planet. Similarly, there is an essential synergy between the different missions for detecting signs of life. For example, TPF-C will measure visible spectra from which the oxygen abundance can be estimated, and TPF-I will measure mid-infrared spectra from which the methane and ozone abundances can be estimated. If these species have abundances like the Earth at some point in its geologic history, then we can infer that the atmosphere is in chemical disequilibrium, which is a strong indicator of life on the planet.

5. Space Interferometer Mission (SIM)

SIM will make an enormously important contribution to exoplanet science. SIM will be able to measure the periodic reflex motions of nearby stars at the sub-microarcsecond level, and thereby measure the masses and 3-D orbits of companion planets. If SIM dedicates about 37% of its mission time to repeatedly measuring these stars, it could detect a 1-Earth-mass planet in the habitable zones of 64 nearby stars within its mission lifetime. The time history of SIM's detections of exoplanets (Figure 3) shows a 2-year startup time during which the astrometric grid is being measured along with the science target stars. Immediately after these data are reduced and orbital motions can be differentiated from parallax and proper motions, then detections of about 39 planets should become immediately apparent (assuming $\eta_{\text{earth}} = 1$, as in all these simulations). Thereafter the detections continue to build to a total of about 64 after 5 years. The exact number of planets detected depends on the detailed observing strategy, which will be determined based on knowledge of η_{earth} obtained by CoRoT and Kepler.

SIM will provide detections of nearby Earths, accurate masses, and accurate 3-D orbits. As shown in Figure 2, this is crucial information for characterizing the planet, when combined with colors and spectra from TPF. This information will also greatly increase the efficiency of TPF by providing an ephemeris for each planet, so observations with TPF can be timed for the best phase angle and elongation values.

6. Scalable Architecture and Science Yield for TPF Missions

In the previous section we identified the scientific vision behind NASA's quest to find other habitable planets and to search for life. To achieve this vision, numerous science teams and working groups have converged on the need to obtain data, over many years, in three different ways, each unique but highly complementary:

- Planet mass and orbital properties from SIM;
- Visible-light photons from TPF-C or -O;
- Infrared photons from TPF-I.

How and when these missions are implemented will depend on the development of key technologies, the availability of funds, and the status of international collaborations. The strategy for the Navigator Program has evolved during this decade for three basic reasons:

- Mounting observational evidence and theoretical analyses in favor of a larger value of η_{earth} than previously assumed, perhaps closer to 1.0 than 0.1. The recently launched CoRoT and then Kepler will determine this value definitively by 2012.
- The funding level for exoplanet missions will be less than was assumed a few years ago;
- The instrumentation for detecting and characterizing Earth-like planets has improved, such that we may now expect to have greater sensitivity and be able to see more planets per star than we had previously thought possible.

In response to these new realities, it is both necessary and possible to consider smaller missions than had previously been contemplated. To estimate the scientific yield of these missions, we first specify some of our assumptions (Table 1) and consider several leading mission concepts (Table 2): TPF-C with either a band-limited mask or shaped pupil; TPF-C with pupil-mapping (PIAA); TPF-O using a 50-m diameter external formation-flying occulter located 72,000 km away from a 4-m telescope; and two designs for TPF-I, either the classic X- array or an Emma X-Array design. Details of these systems are described in individual white papers.

The scientific yield in terms of number of detections of Earth-like or Jupiter-like planets (Table 2) suggests that there could be great value in mid- or probe-scale missions if η_{Earth} is high. Although the number of detected planets is smaller than for large-scale missions, the numbers are still scientifically rewarding. However, at the smallest size (probe-scale) both the number of detections and the degree of physical characterization are diminished. For example, with probes we will probably only be able to measure the color of most planets not a full spectrum. As Fig. 2 indicates, the color of a planet is useful in guessing its character, but a spectrum is essential for determining atmospheric and/or surface composition and searching for signs of life.

A robust program strategy could include combining techniques in order to get the maximum scientific benefit. For example, by planning a dual mission comprising a pupil masking

Table 1. Mission Assumptions for Table 2

- 5-year mission, split approximately between detection (25%), characterization (25%), and general astrophysics (50%).
- η_{Earth} and η_{Jupiter} are both unity
- TPF-C/O operates from 0.6-1 μm
- TPF-I operates from 6.5-18 μm
- Realistic optical efficiencies and overheads are included
- Two types of mission are listed: Earth-searching and Jupiter-searching
- Mission class cost estimates are for development phase in current FY07 dollars.

coronagraph telescope accompanied by an occulter mask, we gain the benefits of each (greater survey capability, and greater characterization capability, respectively), and provide greater combined mission reliability.

- To illustrate the cumulative number of Earth detections as a function of elapsed mission time, Figure 3 shows this relation for each of the mission types in Table 2. While clearly some mission types have greater detection potential than others, the feasibility of each will be determined by technological readiness, cost, risk, and science characterization potential. Trade studies to assess each of these factors are ongoing.

Table 2. Various Versions of TPF in Different Mission Classes					
	Type	IWA* (λ/D_{\max})	Primary Mirror	# Earths, # Targets	# Jupiters, # Targets
Large-class Mission (> \$2B)					
TPF-I	Classic-X Array	2.5	4 @ 4 m plus beam combiner spacecraft	190, 380	440, 460
TPF-C	Flight Baseline-1	4	8 m x 3.5 m	41, 85	390, 680
TPF-C	Flight Baseline-1 with Pupil Mapping (PIAA)	4	8 m x 3.5 m	73, 140	580, 800
Mid-class Mission (< \$2B)					
TPF-I	Emma-X Array	2.5	4 @ 2 m plus beam combiner spacecraft	70, 150	160, 190
TPF-C	Band Limited Mask or Shaped Pupil	3.5	4 m	19, 36	320, 540
TPF-C	Pupil Mapping (PIAA)	3.5	4 m	25, 56	460, 580
TPF-C	Pupil Mapping (PIAA)	2.5	4 m, aggressive IWA	48, 99	550, 710
TPF-O	External Occulter	~2.5	4 m telescope + 50 m occulter @ 72000 km	28, 64	70, 78
Probe-class Mission (< \$1B)					
TPF-C	Band Limited Mask or Shaped Pupil	3.5	2.5 m	6, 13	130, 240
TPF-C	Pupil Mapping (PIAA)	3.5	2.5 m	7, 15	230, 380
TPF-C	Pupil Mapping (PIAA)	2.5	2.5 m, aggressive IWA	16, 29	290, 470

Table 2. The expected number of detected Earths or Jupiters is listed for several types of large-, mid-, and probe-scale missions, at the end of the detection phase of the mission. Numbers of planets over 100 are rounded. See individual white papers for details. *Here “IWA” is inner working angle in units of the angle λ/D_{\max} where D_{\max} is the maximum of telescope diameter or interferometer baseline. The IWA for TPF-O is roughly independent of λ , but for comparison is shown here for a mid-visible wavelength.

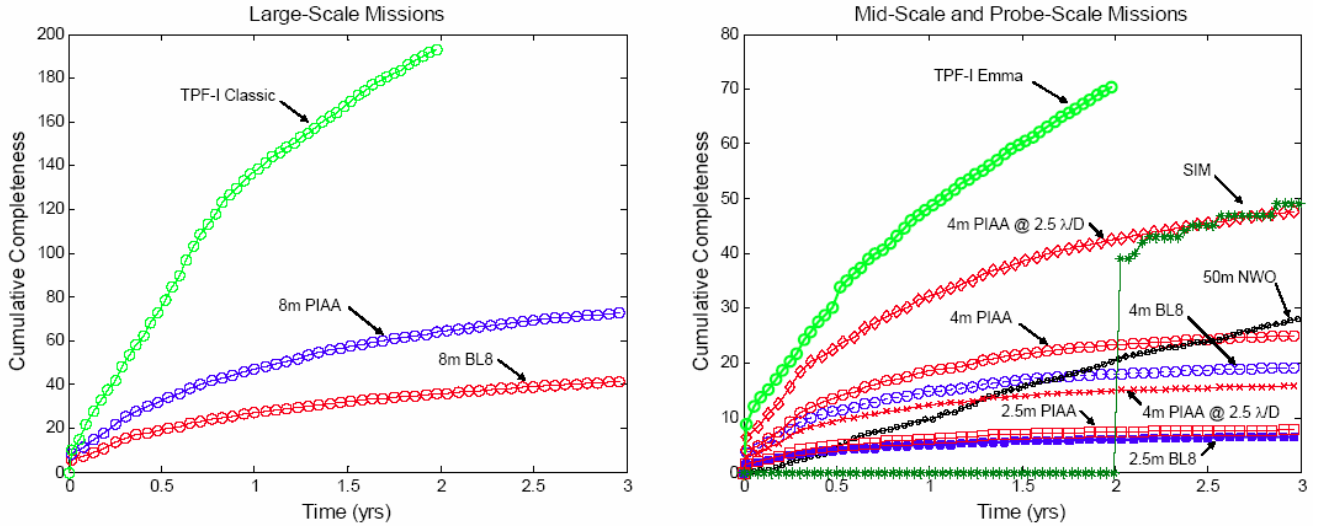


Figure 3. The cumulative number of detected Earths initially increases rapidly with mission time, but begins to level off later, as the individual techniques reach their limits in terms of IWA or magnitude. Here η_{Earth} is unity. The SIM line is flat for 2 years while target- and grid-star observations accumulate, and the grid becomes largely locked up, then a solution for the accumulated data produces about 39 planets immediately, and thereafter those with longer periods are gradually added.

7. Summary and Recommendations

As described in the individual white papers for the various TPF mission concepts, great progress has been made in the fundamental technologies of stellar rejection at visible and infrared wavelengths. With appropriate investment these missions could be ready for launch by the end of the next decade. The technology needed for the SIM mission, subjected to external review, has already been demonstrated.

A strategy for achieving the vision outlined here is as follows:

- 1) Launch SIM in about 2015.
- 2) Launch TPF #1 in 2019, followed by TPF #2 later. These are a coronagraph and/or occulter, and an interferometer, in the full-, mid-, or probe-scale mission size range.
- 3) Collaborate with ESA, and other space agencies, on TPF #1 and #2.
- 4) Support community development through precursor observations, important archives, and a robust research and analysis program via the Origins of Solar Systems, TPF Foundation Science, and the Michelson Fellowship programs.

With these steps NASA will be addressing one of the most profound intellectual questions of all time, “Are We Alone?” using the tools of 21st Century science.